such pumps rated at 18.9 L/min (5 gpm) @15" Hg, are (i) flexible-impeller centrifugal pumps, e.g. Jabsco #30510-2003; (ii) air operated diaphragm pumps, e.g. Wilden M2; (iii) progressing cavity pumps, e.g. Ramoy 3561; and (iv) hosepumps, e.g. Waukesha SP 25.

The skein may also be potted in a header which is not a rectangular prism, preferably in cylindrical upper and lower headers in which substantially concentric arrays of fibers are non-removably potted in cylindrical permeate pans, and the headers are spaced apart by a central gas tube which functions as both the spacer means and the gas-distribution means which is also potted in the headers. As before, the fibers are restrictedly swayable, but permeate is withdrawn from both upper and lower headers through a single permeate pan so that all connections for the skein, when it is vertically submerged, are from above. Permeate is preferably withdrawn from the lower permeate pan through a central permeate withdrawal tube which is centrally axially held within the central gas (air) tube. The concentric arrays are formed by wrapping successive sheets of flat arrays around the central air-tube, and gluing them together before they are potted. This configuration permits the use of more filtration surface area per unit volume of a reservoir, compared to skeins with rectangular prism headers, using the same diameter and length of fibers.

EXAMPLE

Microfiltration of an activated sludge at 30° C. having a concentration of 25 g/L (2.5% TSS) is carried out with a skein of polysulfone fibers in a pilot plant tank. The fibers are "air scrubbed" at a flow rate of 12 CFM (0.34 m^3/min) with a coarse bubble diffuser generating bubbles in the range from about 5 mm to 25 mm in nominal diameter. The air is sufficient not only for the oxidation requirements of the biomass but also for adequate scrubbing. The fibers have an outside diameter of 1.7 mm, a wall thickness of about 0.5 mm, and a surface porosity in the range from about 20% to 40% with pores about 0.2 μm in diameter, both latter physical properties being determined by a molecular weight cut off at 200,000 Daltons. The skein which has 1440 fibers with a surface area of 12 m^2 is wall-mounted in the tank, the vertical spaced apart distance of the headers being about 1% less than the length of a fiber in the skein. The opposed ends of the fibers are potted in upper and lower headers respectively, each about 41 cm long and 10 cm wide. The fixing material of the headers is an epoxy having a hardness of about 70 Shore D with additional upper an lower laminae of softer polyurethane (about 60 Shore A and 30 Shore D respectively) above and below the epoxy lamina, and the fibers are potted to a depth sufficient to have their open ends protrude from the bottom of the header. The average transmembrane pressure differential is about 34.5 kPa (5 psi). Permeate is withdrawn through lines connected to the collection pan of each header with a pump generating about 34.5 kPa (5 psi) suction. Permeate is withdrawn at a specific flux of about 0.7 lm^2h/kPa yielding about 4.8 l/min of permeate which has an average turbidity of <0.8 NTU, which is a turbidity not discernible to the naked eye.

It will now be evident that the membrane device and basic separation processes of this invention may be used in the recovery and separation of a wide variety of commercially significant materials, some of which, illustratively referred to, include the recovery of water from ground water containing micron and submicron particles of siliceous materials, preferably "gas scrubbing" with carbon dioxide; or, the recovery of solvent from paint-contaminated solvent. In each application, the choice of membrane will depend upon the physical characteristics of the materials and the separation desired. The choice of gas will depend on whether oxygen is needed in the substrate.

In each case, the simple process comprises, disposing a skein of a multiplicity of hollow fiber membranes, or fibers each having a length >0.5 meter, together having a surface area >1 m^2, in a body of substrate which is unconfined in a modular shell, so that the fibers are essentially restrictedly swayable in the substrate. The substrate is typically not under pressure greater than atmospheric. The fibers have a low transmembrane pressure differential in the range from about 3.5 kPa (0.5 psi) to about 350 kPa (50 psi), and the headers, the terminal portions of the fibers, and the ends of the fibers are disposed in spaced-apart relationship as described hereinabove, so that by applying a suction on the aft face of at least one of the headers, preferably both, permeate is withdrawn through the collection means in which each header is mounted in fluid-tight communication.

Having thus provided a general discussion, and specific illustrations of the best mode of constructing and deploying a membrane device comprising a skein of long fibers in a substrate from which a particular component is to be produced as permeate, how the device is used in a gas-scrubbed skein, and having provided specific illustrative systems and processes in which the skein is used, it is to be understood that no undue restrictions are to be imposed by reason of the specific embodiments illustrated and discussed, and particularly that the invention is not restricted to a slavish adherence to the details set forth herein.

We claim:

1. In a microfiltration membrane device, for withdrawing permeate essentially continuously from a multicomponent liquid substrate while increasing the concentration of particulate material therein, said membrane device including:

a multiplicity of hollow fiber membranes, or fibers, unconfined in a shell of a module, said fibers together having a surface area >1 m^2, said fibers being swayable in said substrate, said fibers being subject to a transmembrane pressure differential in the range from about 0.7 kPa (0.1 psi) to about 345 kPa (50 psi), and each fiber having a length >0.5 meter;

a first header and a second header disposed in transversely spaced-apart relationship with said second header within said substrate;

said first header and said second header having opposed terminal end portions of each fiber sealingly secured therein, all open ends of said fibers extending from a permeate-discharging face of at least one header;

permeate collection means to collect said permeate, sealingly connected in open fluid communication with a permeate-discharging face of each of said headers;

and, means to withdraw said permeate;

the improvement comprising,

said fibers, said headers and said permeate collection means together forming a vertical skein wherein said fibers are essentially vertically disposed and terminal end portions of individual fibers are potted in proximately spaced-apart relationship in cured resin;

said first header being upper and disposed in vertically spaced-apart relationship above said second header, with opposed faces at a fixed distance;

each of said fibers having substantially the same length, said length being from 0.1% to less than 5% greater than said fixed distance so as to permit restricted displacement of an intermediate portion of each fiber, independently of the movement of another fiber.

2. The membrane device of claim 1 wherein each said header is a mass of synthetic resinous material in which said terminal end portions are potted and said fibers are formed from an organic resinous material or a ceramic.

3. The membrane device of claim 2 wherein each said hollow fiber has an outside diameter in the range from about 20 μm to about 3 mm, a wall thickness in the range from about 5 μm to about 2 mm, and, said fiber is formed from a material selected from the group consisting of natural and synthetic polymers, and pore size in the range from 1000 Å to 10000 Å, and, said displacement is in the lateral or horizontal direction.

4. The membrane device of claim 3 wherein said transmembrane pressure differential is in the range from 3.5 kPa (0.5 psi) to about 175 kPa (25 psi), said fibers are in the range from 0.5 m to 5 m long, and said terminal end portions of said fibers are potted within said mass of thermosetting synthetic resinous material to a depth in the range from about 1 cm to about 5 cm.

5. The membrane device of claim 3 wherein said substrate is maintained at a pressure in the range from about 1–10 atm, said fibers extend as a skein upwardly from a fiber-supporting face of each of said headers, each header is a rectangular prism having substantially the same dimensions, said fibers extend downwardly through the permeate-discharging face of said headers, and said permeate is discharged upwardly relative to said upper header.

6. The membrane device of claim 4 wherein said terminal end portions of said fibers are potted within a mass of thermosetting synthetic resinous material to a depth in the range from about 1 cm to about 5 cm and protrude through a permeate-discharging face of each said header in a range from about 0.1 mm to about 1 cm.

7. The membrane device of claim 6 wherein said open ends of fibers are bounded by a geometrically regular peripheral boundary around the outermost peripheries of the outermost fibers in the boundary, and the length of a fiber is essentially independent of the strength of said fiber, or its diameter.

8. The membrane device of claim 7 wherein said fibers together have a surface area in the range from 10 to 10^3 m^2.

9. The membrane device of claim 8 wherein said first and second headers are each a rectangular parallelpiped and said first header is disposed parallel to said second header.

10. In a gas-scrubbed assembly comprising, a microfiltration membrane device in combination with a gas-distribution means to minimize build-up of particulate deposits on the surfaces of hollow fiber membranes ("fibers") in said device, and to recover permeate from a multicomponent liquid substrate while leaving particulate matter therein, said membrane device comprising,

a multiplicity of fibers, unconfined in a shell of a module, said fibers together having a surface area >1 m^2, said fibers being swayable in said substrate, said fibers being subject to a transmembrane pressure differential in the range from about 0.7 kPa (0.1 psi) to about 345 kPa (50 psi), and each having a length >0.5 meter;

a first and second header disposed in spaced-apart relationship within said substrate;

said first header and said second header having opposed terminal end portions of each fiber sealingly secured therein, all open ends of said fibers extending from a permeate-discharging face of at least one header;

permeate collection means to collect said permeate, sealingly connected in open fluid communication with a permeate-discharging face of each of said headers; and,

means for withdrawing said permeate; and,

said gas-distribution means is located within a zone near the base of said skein, having through-passages therein adapted to have sufficient gas flowed therethrough to generate enough bubbles flowing in a column of rising bubbles through and around said skein fibers, to keep surfaces of said fibers awash in bubbles;

the improvement comprising,

said fibers, said headers and said permeate collection means together forming a skein wherein said fibers are essentially vertically disposed and terminal end portions of individual fibers are potted in proximately spaced-apart relationship in cured resin;

said first header being upper and disposed in vertically spaced-apart relationship above said second header at a fixed distance;

each of said fibers having substantially the same length, said length being from at least 0.1% greater, to less than 5% greater than said fixed distance so as to permit restricted displacement of an intermediate portion of each fiber, independently of the movement of another fiber; and,

said gas distribution means having through-passages therein to discharge a cleansing gas in an amount in the range from 0.47–14 cm^3/sec per fiber (0.001 scfm/fiber to about 0.03 scfm/fiber) in a column of bubbles which rise vertically substantially parallel to, and in contact with said fibers, movement of which is restricted within said column;

whereby said permeate is essentially continuously withdrawn while concentration of said particulate matter in said substrate is increased.

11. The gas-scrubbed assembly of claim 10 wherein said fixed distance is adjustable, said gas-distribution means includes at least two distribution means disposed, one on each side of said skein, said gas-distribution means generate bubbles having an average diameter in the range from about 0.1 mm to about 25 mm which bubbles contact said fibers, maintain their buoyancy, and maintain said fibers' outer surfaces essentially free from build-up of deposits of said particulate matter.

12. The gas-scrubbed assembly of claim 11 wherein said through-passages in said gas-distribution means generate bubbles in the size range from 1 mm to 25 mm in relatively close proximity, in the range from 1 cm to about 50 cm, to said through-passages.

13. The gas-scrubbed assembly of claim 10 wherein said fibers have pores in the size range from about 1000 Å to 10000 Å, each said header is a rectangular prism having substantially the same dimensions, said gas is an oxygen-containing gas, and said particulate matter comprises biologically active microorganisms growing in said substrate.

14. The gas-scrubbed assembly of claim 10 wherein said particulate matter comprises finely divided inorganic particles.

15. In a process for maintaining the outer surfaces of hollow fiber membranes essentially free from a build-up of deposits of particulate material while separating a permeate from a multicomponent liquid substrate in a reservoir, said process comprising,

submerging skein fibers within said substrate unconfined in a modular shell, said fibers being securely held in laterally opposed, spaced-apart first and second headers, said fibers having a transmembrane pressure differential in the range from about 0.7 kPa (0.1 psi) to about 345 kPa (50 psi), a total surface area >1 m^2, and a length sufficiently greater than the direct distance

between opposed faces of said first and second headers, so as to present said skein in a swayable configuration above a horizontal plane through the horizontal centerline of a header;

mounting said headers in fluid-tight open communication with collection means to collect said permeate;

flowing a fiber-cleansing gas through a gas-distribution means proximately disposed relative to said skein, within a zone near the base of said skein, and contacting surfaces of said fibers with sufficient physical impact of bubbles of said gas to maintain essentially the entire length of each fiber in said skein awash with bubbles and essentially free from said build-up;

maintaining an essentially constant flux through said fibers substantially the same as an equilibrium flux initially obtained after commencing operation of said process;

collecting said permeate in said collection means; and,

withdrawing said permeate,

the improvement comprising,

introducing a cleansing gas in an amount in the range from 0.47–14 cm^3/sec per fiber (0.001 scfm/fiber to about 0.03 scfm/fiber) to generate a column of said bubbles alongside and in contact with outer surfaces of said fibers;

deploying said skein fibers within said column in an essentially vertical configuration, with said headers in fixed spaced apart relationship at a fixed distance, said skein having fibers of substantially the same length and from at least 0.1% greater, to about 5% greater than said fixed distance, said fibers being independently swayable from side-to-side within a vertical zone of movement with terminal end portions of individual fibers potted in proximately spaced-apart relationship in cured resin;

restricting movement of said fibers to said vertical zone defined by lateral movement of outer fibers in said skein;

vertically gas-scrubbing said fibers' outside surfaces with bubbles which flow upward in contact with said surfaces;

maintaining said surfaces substantially free from said deposits of particulate matter during a period when specific flux through said fibers has attained equilibrium; and,

simultaneously, essentially continuously, withdrawing said permeate while increasing the concentration of said particulate material in said substrate.

16. The process of claim 15 wherein each said hollow fiber has an outside diameter in the range from about 20 μm to about 3 mm, and a wall thickness in the range from about 5 μm to about 1 mm; each said header is formed from a mass of thermosetting or thermoplastic synthetic resinous material; terminal end portions of said fibers are potted within said resinous material to a depth in the range from about 1 cm to about 5 cm;

said particulate matter is selected from the group consisting of microorganisms and finely divided inorganic particles; and,

said gas-distribution means generates bubbles having an average diameter in the range from about 1 mm to about 25 mm.

17. A method of forming a header for a skein of a multiplicity of fibers, comprising,

forming a stack of at least two superimposed essentially coplanar and similar arrays, each array comprising a chosen number of fibers supported on a support means having a thickness corresponding to a desired lateral spacing between adjacent arrays;

holding the stack in a first liquid with terminal portions of the fibers submerged, until the liquid solidifies into a first shaped lamina, provided that the first liquid is unreactive with material of the fibers;

pouring a second liquid over the first shaped lamina to embed the fibers to a desired depth, and solidifying the second liquid to form a fixing lamina upon the first shaped lamina, the second liquid also being substantially unreactive with either the material of the fibers or that of the first shaped lamina;

forming a composite header in which terminal portions of the fibers are potted, the composite header comprising a laminate of a fugitive lamina of fugitive material and a contiguous finished header of fixing lamina; and,

removing the first shaped lamina without removing a portion of the fixing lamina so as to leave the ends of the fibers open and protruding from the aft face of the header,

whereby the open ends having a circular cross-section are exposed without cutting the fibers.

18. The method of claim 17 wherein said second liquid upon solidification forms a thermosetting or thermoplastic synthetic resin, and said first liquid upon solidification forms a solid which has a melting point or glass transition temperature lower than the melting point or glass transition temperature of said synthetic resin.

19. The method of claim 18 wherein said first liquid upon solidification is flowable at a temperature at which said second liquid upon solidification remains solid.

20. The method of claim 18 wherein said first liquid upon solidification is soluble in a chosen solvent, and said second liquid upon solidification is insoluble in said solvent.

21. A header in which a multiplicity of hollow fiber membranes or "fibers" is potted, said header comprising,

a molded body of arbitrary shape striated in a fixing lamina and a fugitive lamina, said fugitive lamina formed from a fugitive potting material and said fixing lamina formed from a fixing material;

said fibers having terminal portions thereof potted in said fugitive potting material which when solidified plugs ends of said fibers, plugged ends having an essentially circular cross-section, said fugitive lamina maintaining said ends in closely spaced-apart substantially parallel relationship;

said fugitive lamina having an aft face towards which said plugged ends protrude, and a fore face through which said fibers extend vertically;

said fugitive lamina having said fixing lamina adhered thereto, said fixing lamina having a thickness sufficient to maintain said fibers in substantially the same spaced-apart relationship relative to one and another as the spaced-apart relationship in said lower portion.

22. The header of claim 21 wherein said fixing lamina has a cushioning lamina embedding said fibers and coextensively adhered to said fixing lamina, said fixing lamina has a hardness in the range from about Shore D 50 to Rockwell R 110, and said cushioning layer has a hardness in the range from Shore A 30 to Shore D 45.

23. In a microfiltration membrane device, for withdrawing permeate essentially continuously from a multi-component liquid substrate while increasing the concentration of particulate material therein, said membrane device including:
a multiplicity of hollow fiber membranes, or fibers, unconfined in a shell of a module, said fibers together having a surface area > 1 m^2, said fibers being swayable in said substrate, said fibers being subject to a transmembrane pressure differential in the range from about 0.7 kPa (0.1 psi) to about 345 kPa (50 psi), and each fiber having length > 0.5 meter;
a first header and a second header having opposed terminal end portions of each fiber sealingly secured therein, all open ends of said fibers extending from a permeate-discharging face of at least one header;
permeate-collection means to collect said permeate, sealingly connected in open fluid communication with a permeate-discharging face of each of said headers;
and, means to withdraw said permeate;
the improvement comprising,
said fibers, said headers and said permeate collection meas together forming a vertical skein wherein said fibers are essentially vertically disposed and terminal end portions of individual fibers are potted in proximately spaced-apart relationship in cured resin;
said first header being upper and disposed in vertically

spaced-apart relationship above said second header, with opposed faces at a fixed distance;
each of said fibers having substantially the same length, said length being from between 0.1% to less than 5% greater than said fixed distance so as to permit restricted displacement of an intermediate portion of each fiber, independently of the movement of another fiber; and,
a gas distribution system having through-passages adapted to discharge bubbles near to rise through or around the skein of fibers, the gas distribution system including one or more gas tubes which space the first and second headers apart and which also carry air to the through-passages.

24. The device of claim 23 wherein the upper and lower headers are cylindrical and the one or more gas tubes are a single gas tube located in about the center of the headers.

25. In a microfiltration membrane device, for withdrawing permeate essentially continuously from a multi-component liquid substrate while increasing the concentration of particulate material therein, said membrane device including:
a multiplicity of hollow fiber membranes, or fibers, unconfined in a shell of a module, said fibers together having a surface area > 1 m^2, said fibers being swayable in said substrate, said fibers being subject to a transmembrane pressure differential in the range from about 0.7 kPa (0.1 psi) to about 345 kPa (50 psi), and each fiber having length > 0.5

meter;

a first header and a second header having opposed terminal end portions of each fiber sealingly secured therein, all open ends of said fibers extending from a permeate-discharging face of at least one header;

permeate-collection means to collect said permeate, sealingly connected in open fluid communication with a permeate-discharging face of each of said headers;

and, means to withdraw said permeate;

the improvement comprising,

said fibers, said headers and said permeate collection meas together forming a vertical skein wherein said fibers are essentially vertically disposed and terminal end portions of individual fibers are potted in proximately spaced-apart relationship in cured resin;

said first header being upper and disposed in vertically spaced-apart relationship above said second header, with opposed faces at a fixed distance;

each of said fibers having substantially the same length, said length being from between 0.1% to less than 5% greater than said fixed distance so as to permit restricted displacement of an intermediate portion of each fiber, independently of the movement of another fiber,

wherein the headers are rectangular in plan view and the skein has about 30 or less arrays of fibers.

26. A device for withdrawing permeate from a

multicomponent liquid substrate comprising,

(a) a reservoir under essentially ambient pressure having a feed zone for containing a substrate;

(b) a microfiltration membrane device, for withdrawing permeate essentially continuously from the multi-component liquid substrate while increasing the concentration of particulate material therein, said membrane device including:

a multiplicity of hollow fiber membranes, or fibers, unconfined in a shell of a module, said fibers together having a surface area > 1 m^2, said fibers being swayable in said substrate, said fibers being subject to a transmembrane pressure differential in the range from about 0.7 kPa (0.1 psi) to about 345 kPa (50 psi), and each fiber having length > 0.5 meter;

a first header and a second header having opposed terminal end portions of each fiber sealingly secured therein, all open ends of said fibers extending from a permeate-discharging face of at least one header;

permeate-collection means to collect said permeate, sealingly connected in open fluid communication with a permeate-discharging face of each of said headers;

and, means to withdraw said permeate;

said fibers, said headers and said permeate collection meas together forming a vertical skein wherein said fibers are essentially vertically disposed and terminal end portions of individual fibers are potted in proximately spaced-apart

relationship in cured resin;

said first header being upper and disposed in vertically spaced-apart relationship above said second header, with opposed faces at a fixed distance;

each of said fibers having substantially the same length, said length being from between 0.1% to less than 5% greater than said fixed distance so as to permit restricted displacement of an intermediate portion of each fiber, independently of the movement of another fiber,

the outside of the membranes in fluid communication with the feed zone of the reservoir;

c) a pump in fluid communication with the insides of the membranes through the permeate collection means, the pump operable to supply a suction to the lumens of the hollow fiber membranes to draw permeate through the membranes; and,

(d) a gas distribution means including a plurality of through-passages for discharging bubbles which rise and contact fibers.

27. The device of claim 26 wherein at least some of the through-passages have outlets located within the skein.

28. The device of claim 26 wherein the headers are rectangular in plan view and have about 30 arrays or less of fibers and the outlets of the through-passages are located to the side of the headers.

29. In a microfiltration membrane device, for withdrawing permeate essentially continuously from a multi-component liquid substrate while increasing the concentration of particulate material therein, said membrane device including: a multiplicity of hollow fiber membranes, or fibers, unconfined in a shell of a module, said fibers together having a surface area $> 1\ m^2$, said fibers being swayable in said substrate, said fibers being subject to a transmembrane pressure differential in the range from about 0.7 kPa (0.1 psi) to about 345 kPa (50 psi), and each fiber having length > 0.5 meter;

a first header and a second header having opposed terminal end portions of each fiber sealingly secured therein, all open ends of said fibers extending from a permeate-discharging face of at least one header;

permeate-collection means to collect said permeate, sealingly connected in open fluid communication with a permeate-discharging face of each of said headers;

and, means to withdraw said permeate;

the improvement comprising,

said fibers, said headers and said permeate collection meas together forming a vertical skein wherein said fibers are essentially vertically disposed and terminal end portions of individual fibers are potted in proximately spaced-apart relationship in cured resin;

said first header being upper and disposed in vertically spaced-apart relationship above said second header, with

opposed faces at a fixed distance;

each of said fibers having substantially the same length, said length being from between 0.1% to less than 5% greater than said fixed distance so as to permit restricted displacement of an intermediate portion of each fiber, independently of the movement of another fiber;

walls extending downwards from a lower header of the first and second header, the walls being adapted to retain a gas below the lower header; and,

through-passages for gas to pass through the lower header from an area below the lower header bordered by the walls.

30. The device of claim 29 wherein the through passages are located such that gas flowing from the area below the lower header bordered by the walls, exits between fibers.

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